Changes in CSF flow after one-stage posterior vertebral column resection in scoliosis patients with syringomyelia and Chiari malformation Type I

Clinical article

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Object. Phase contrast–cine MRI (PC-cine MRI) studies in patients with syringomyelia and Chiari malformation Type I (CM-I) have demonstrated abnormal CSF flow across the foramen magnum, which can revert to normal after craniocervical decompression with syrinx shrinkage. In order to investigate the mechanisms leading to postoperative syringomyelia shrinkage, the authors studied the hydrodynamic changes of CSF flow in the craniocervical junction and spinal canal in patients with scoliosis associated with syringomyelia after one-stage deformity correction by posterior vertebral column resection.

Methods. Preoperative and postoperative CSF flow dynamics at the levels of the foramen magnum, C-7, T-7 (or apex), and L-1 were assessed by electrocardiogram-synchronized cardiac-gated PC-cine MRI in 8 adolescent patients suffering from severe scoliosis with syringomyelia and CM-I (scoliosis group) and undergoing posterior vertebral column resection. An additional 8 patients with syringomyelia and CM-I without spinal deformity (syrinx group) and 8 healthy volunteers (control group) were also enrolled. Mean values were obtained for the following parameters: the duration of a CSF cycle, the duration of caudad CSF flow (CSF downflow [DF]) and cephalad CSF flow (CSF upflow [UF]), the ratio of DF duration to CSF cycle duration (DF%), and the ratio of UF duration to CSF cycle duration (UF%). The ratio of the stationary phase (SP) duration to CSF cycle duration was calculated (SP%). The maximum downflow velocities (VDmax) and maximum upflow velocities (VUmax) were measured. SPSS (version 14.0) was used for all statistical analysis.

Results. Patients in the scoliosis group underwent one-stage posterior vertebral column resection for deformity correction without suboccipital decompression. The mean preoperative coronal Cobb angle was 102.4° (range 76°–138°). The mean postoperative Cobb angle was 41.7° (range 12°–75°), with an average correction rate of 59.3%. During the follow-up, 1 patient with hypermyotonia experienced a significant decrease of muscle tension and 1 patient with reduced anal sphincter tone manifested recovery. A total of 5 patients demonstrated a significant decrease (>30%) in syrinx size. With respect to changes in CSF flow dynamics, the syrinx group was characterized by slower and shorter downflow than the control group, and the difference was more significant at the foramen magnum and C-7 levels. In patients with scoliosis, CSF downflow at the foramen magnum level was significantly restricted, and a prolonged stationary phase indicated increased obstruction of CSF flow. After posterior vertebral column resection, the peak velocity of CSF flow at the foramen magnum increased, and the downflow phase duration was markedly prolonged. The parameters showed a return to almost normal CSF dynamics at the craniocervical region, and this improvement was maintained for 6–12 months of follow-up.

Conclusions. There were distinct abnormalities of CSF flow at the craniocervical junction in patients with syringomyelia. Abnormal dynamics of downflow could be aggravated by associated severe spinal deformity and improved by correction via posterior vertebral column resection.

(10.3171/2013.1.SPINE12366)

Key Words • syringomyelia • scoliosis • cerebrospinal fluid • magnetic resonance imaging • posterior vertebral column resection • deformity

Chiari malformation Type I is defined as cerebellar tonsillar descent below the foramen magnum and into the spinal canal. It is the leading cause of syringomyelia, which is characterized by a fluid-filled cavity within the substance of the spinal cord. Syringomyelia associated with CM-I is often limited to the cervical region of the spinal cord, although it may extend to the thoracic portion. The exact pathogenesis of syringomyelia...
in patients with CM-I has not been clarified. Disturbed or obstructed CSF flow around the foramen magnum was assumed to be the primary cause.\textsuperscript{3,4} Pathological CSF flow at the foramen magnum and cervical spinal canal has been demonstrated by PC-cine MRI studies in patients with CM-I and syringomyelia.\textsuperscript{7,10}

Phase contrast–cine MRI enables analysis of CSF flow patterns and dynamic changes during a cardiac cycle. Research using PC-cine MRI has shown that patients with CM-I have significantly abnormal CSF flow in the spinal subarachnoid space of the craniocervical junction.\textsuperscript{2,20} Indeed, presenting symptomology has been defined to correlate with the degree of hindbrain CSF flow obstruction rather than the degree of tonsillar ectopia in patients with CM-I.\textsuperscript{7} Following posterior neurological decompression, abnormal CSF flow can revert to normal, with symptomatic improvement, and syringomyelia may continue to diminish for months to years after the operation.\textsuperscript{14,24} However, the correlation between CSF flow dynamics and syringomyelia resolution requires further investigation.\textsuperscript{25}

In recent years, more studies have confirmed that the prevalence of syringomyelia associated with scoliosis was higher than previously thought.\textsuperscript{18} However, the etiological connection between syringomyelia and scoliosis is unclear. Some reports state that the pressure from an asymmetrically expanding syrinx may be imparted to the ventromedial nuclei, affecting the cells that innervate the trunk musculature and thus causing the imbalance that leads to scoliosis. However, this does not explain why CM-I patients without syringomyelia also suffer from scoliosis.\textsuperscript{21,29} Moreover, clinical studies have revealed that whether patients present with or without syrinx-related neurological symptoms, symptom severity and syrinx size, shape, and progression are not related to the pattern or progression of the scoliotic curve.\textsuperscript{26} Besides, if pediatric patients with CM-I and syringomyelia undergo neurological decompression surgery before they reach 11–12 years of age, there is a high probability of spontaneous improvement of syringomyelia following complete or partial resolution of the syrinx, whereas if decompression is performed after patients reach 12 years of age, scoliosis tends to progress over time.\textsuperscript{6}

For adolescent patients with large-curve scoliosis and CM-I and syringomyelia, traditional theories advocate that decompression of craniocervical bone and posterior fossa elements and shunting of the syrinx should be performed prior to spinal fusion, to improve neurological safety. Because of the considerations that 1) almost all moderate or severe spinal deformities associated with CM-I in adolescents needed further correction after decompression, and 2) posterior vertebral column resection can effectively shorten spine and reduce the tension of spinal cord, we reported on a series of patients who underwent one-stage posterior vertebral column resection for scoliosis correction without suboccipital decompression.\textsuperscript{27} There was no iatrogenic neurological deterioration, and even more importantly, we observed a gradual reduction in syrinx size following posterior vertebral column resection procedures.

To the best of our knowledge, no report has involved the hydrodynamic changes of CSF flow at the craniocervical junction and cervical spinal canal in patients with scoliosis associated with syringomyelia and CM-I. We therefore designed the present study to analyze 8 cases involving scoliosis patients with syringomyelia and CM-I, who underwent surgery for correction of spinal deformities at the authors’ institution. We compared findings in these 8 patients with findings in patients with syringomyelia and CM-I without scoliosis and with measurements obtained in healthy volunteers. Phase contrast–cine MRI scans before and after one-stage posterior vertebral column resection correction procedures were obtained in all 8 patients, and the features of CSF flow dynamics were studied quantitatively. We paid special attention to CSF flow dynamic changes after posterior vertebral column resection in order to investigate the mechanisms leading to postoperative reduction in syrinx size.

**Methods**

**Patient and Control Groups**

The scoliosis group consisted of 8 adolescents with large-curve scoliosis with syringomyelia and CM-I who were surgically treated in our institution between December 2008 and December 2010. Eight patients with CM-I and syringomyelia, without scoliosis, who were hospitalized for neurosurgical treatment during the same period were also enrolled (syrinx group), and 8 healthy volunteers made up the control group.

The mean age of the 8 patients in the scoliosis group (3 male and 5 female) was 14.7 years (range 12–18 years). Of these patients, 5 were found to have neurological abnormalities, including asymmetrical abdominal reflexes and hyperreflexia of the lower extremities (4 patients), hypermyotonia of the lower extremities (2 patients), and reduced anal sphincter tone (1 patient). All patients in the scoliosis group underwent one-stage posterior vertebral column resection for correction of the spinal deformities, and the outcomes were recorded at 3 weeks, 6 months, and 1 year postoperatively as well as at the most recent follow-up examination.

The mean age of the 8 patients in the syrinx group (5 male and 3 female) was 11.3 years (range 6–17 years). Patients in the syrinx group presented with headache or neck pain (all 8 patients), continuously enlarging syrinx (2 patients), and demonstrated sensory dissociation (5 patients) and asymmetrical abdominal or lower-extremity reflexes (2 patients). Chest radiography was performed for routine evaluation before neurosurgical operation and in order to exclude scoliosis.

The mean age of the control group (5 male and 3 female volunteers) was 15.5 years (range 12–24 years). In all patients with syringomyelia and CM-I, CM-I was diagnosed via MRI with the inclusion criterion of cerebellar tonsillar descent more than 5 mm below the inferior margin of the foramen magnum. The MRI examinations were performed with a 1.5-T MR scanner (Sonata, Siemens) using cervical and spinal coils. Standard imaging of the brain and spinal cord—including sagittal and axial T1-weighted, and, in most cases, axial T2-weighted

\footnotesize{J Neurosurg: Spine / Volume 18 / May 2013}
sequences—was performed to evaluate the extent and diameters of the syringes. Patients with hydrocephalus, combined congenital malformation at the craniovertebral junction such as basilar invagination or assimilation of the atlas, diastematomyelia, tethered cord, or tumor or infection of the spinal canal were excluded. In the scoliosis group, standing AP radiographs and lateral-flexion radiographs of the full length of the spine were obtained to assess the shape and flexibility of the spinal curve. In addition, 3D CT was used to exclude congenital factors contributing to scoliosis.

**Phase Contrast–Cine MRI**

In the scoliosis group, PC-cine MRI scans were performed preoperatively and 3 weeks and 6 or 12 months postoperatively. Patients in the syrinx group underwent PC-cine MRI examinations before neurosurgery. Each volunteer in the control group underwent a single PC-cine MRI examination.

The PC-cine MRI scans started when the patients or controls had achieved a steady heart rate with quiet respiration. Synchronized cardiac gating was used to divide the cardiac cycle into 32–48 images. Cerebrospinal fluid flow studies were performed at the levels of the foramen magnum, C-7, T-7 (or apical spine), and L-1 in the axial plane with the following sequence: TR 32–50 msec (depending on heart rate)/TE 6.9 msec, flip angle 20°, slice thickness 3 mm, matrix 256 × 196, and encoding velocity 20 cm/sec. The section orientation was axial and perpendicular to the spinal canal, and section locations were chosen at the inferior margin of foramen magnum and middle portion of the vertebral bodies. Because of the signal interference from the instrumentation, axial T-7 and L-1 scans were not obtained postoperatively in scoliosis patients. In phase-contrast images, low signal intensity indicated caudal CSF flow (downflow), whereas high signal intensity indicated cranial flow (upflow). The signal intensity represented the velocity of CSF flow.

The acquired phase-contrast images were transferred to an Argus postprocessing program (Siemens) for CSF flow analysis. Regions of interest were selected in the axial plane: 4 regions of interest were evenly placed at the anterior and posterior subarachnoid space for the foramen magnum and the cervical, thoracic, and lumbar spine. Cerebrospinal fluid flow changes throughout one cardiac cycle were extracted automatically from the program by velocity–time, peak velocity–time, flow–time, and net flow–time graphics. The velocity-time curves and peak velocity–time curves of healthy controls revealed that, in the cardiac systolic phase, the CSF flow was mainly in the caudal direction, and in the diastolic phase, mainly in the cranial direction. During a CSF flow cycle which corresponded to a cardiac cycle, first CSF flow showed a stationary phase (SP) duration (SP%) were calculated. The maximum downflow velocities (VD_{max}) and maximum upflow velocities (VU_{max}) were also measured.

**Posterior Vertebral Column Resection**

We performed one-stage posterior vertebral column resection for correction of spinal deformities in all patients in the scoliosis group. The procedure was performed as previously reported and included resection of the osseous elements posterior and anterior to one or more spinal segments as well as the upper and lower vertebral discs adjacent to the segments. This created sufficient space in which correction and reconstruction could be performed. During the correction procedures, the corrective forces were mainly applied as compression though the spinal column. Along with the shortening of the vertebral column, this helped to avoid excessive stretching or displacement of the spinal cord. After deformity correction and tightening of instrumentation, titanium mesh or cancellous autograft was used to fill into the residual gap for anterior fusion.

**Statistical Analysis**

Statistical analysis was performed using the Statisti-
CSF flow in scoliosis patients with CM-I and syringomyelia

Critical Package for the Social Sciences 14.0 (SPSS). Quantitative data were calculated as mean ± standard deviation. An independent samples t-test was used for comparison between groups, and a paired t-test for comparison within a group. Statistical significance was defined as p < 0.05.

Results

Features of Syringomyelia and Spinal Deformities

All patients in the scoliosis group and the syrinx group presented with syringomyelia. In the patients in the scoliosis group, the syringes were between the C-2 and the T-10 level, each involving 3–12 spinal segments, with the maximum AP diameter of the syrinx most often in the lower cervical cord. Measured on the axial plane, the ratio of the maximum AP diameter of the syrinx to the AP diameter of the cervical canal (ratio of syrinx to cord diameter), expressed as a percentage, averaged 43.5% (range 12.0%–63.0%). In patients in the syrinx group, the syringes were between C-3 and T-6 and involved 3–9 spinal segments, mostly in the lower cervical cord. Chiari malformation was diagnosed by spine surgeons together with neurosurgeons in all 16 patients.

In the scoliosis group, the location of the apex of the scoliotic curve ranged from T-6 to T-12. The average preoperative coronal Cobb angle was 102.4° (range 76°–138°). The average Cobb angle after the posterior vertebral column resection procedure was 41.7° (range 12°–75°), with an average correction rate of 59.3%. At 3 weeks after surgery, no patients presented with new neurological deficits or deterioration of their original neurological abnormalities. Compared with preoperative measurements, the length of the syrinx was not significantly changed in any of the 8 patients, but there was a significant reduction (> 30%) in the syrinx diameter in 4 patients (Fig. 2).

The average duration of follow-up for patients in the scoliosis group was 18.6 months (range 12–36 months). The patients underwent PC-cine MRI at 6 or 12 months after surgery. Compared with the results of preoperative evaluation, there was no difference in the presence of asymmetrical abdominal reflexes. However, 1 patient with hypermyotonia experienced a significant decrease in muscle tension, and 1 patient with reduced anal sphincter tone manifested recovery. A total of 5 patients had a significant decrease (> 30%) in syrinx diameter in 4 patients (Fig. 2).

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Phase Contrast–Cine MRI Findings

Control Group. In the present study, the results we obtained in healthy volunteers showed that the pattern of CSF flow change in the peak velocity–time graph was similar to a sinusoid curve. Dynamic parameters measured at the foramen magnum, C-7, and T-7 levels revealed that there was no significant difference between the peak velocities of downflow and upflow at each level, and the upflow phase was longer than the downflow phase. At the L-1 level, the duration of upflow was significantly longer than that of upflow and the downflow peak velocity was much higher than the upflow peak velocity.

Syrinx Group. In patients with syringomyelia and CM, the peak upflow velocities at the foramen magnum and C-7 levels were larger than the peak downflow velocities, with duration of upflow being longer than that of downflow. Compared with the control group, the syrinx group had significantly lower peak velocities of CSF flow at the foramen magnum and C-7 level and the downflow duration was significantly shorter. The stationary phase was longer at the foramen magnum level in the syrinx group than in the control group (Table 1).

Scoliosis Group—Preoperative Findings. In patients with scoliosis and syringomyelia, the peak velocities of CSF flow showed a gradually increasing trend from the foramen magnum to C-7 and the apical vertebra. The upflow duration was longer than downflow duration at the foramen magnum, C-7, and T-7 levels. Compared with the control group, the scoliosis group had significantly greater peak velocities of both up- and downflow at the middle thoracic spine (T-7/ apex) and decreased peak downflow velocities at the foramen magnum. The duration of both up- and downflow at all the imaging levels in the scoliosis group was not significantly different from the duration in the control group; the stationary phase at the foramen magnum level, however, was prolonged. Compared with syrinx group, the scoliosis group had significantly greater peak velocities for both up- and downflow at the middle thoracic spine, but there was no significant difference between the groups with respect to peak velocities at the foramen magnum and C-7 levels. The duration of upflow at the foramen magnum and downflow at C-7 level differed significantly between the scoliosis and syrinx groups. Moreover, the stationary phase at the foramen magnum level was longer in the scoliosis group than in the syrinx group (Tables 2 and 3).

Scoliosis Group—Postoperative Findings. Studies of CSF flow change at 3 weeks after operation after operation revealed that, compared with preoperative values, the peak velocities of both up- and downflow were increased at the foramen magnum level, with increased downflow duration, and decreased ratio of duration of upflow to downflow. At the 6- or 12-month follow-up examination, there was no significant difference in the parameters compared with values obtained 3 weeks postoperatively, and the peak velocities of both up- and downflow were increased at the foramen magnum level compared with preoperative values (Fig. 3 and Table 4).

Discussion

In the present study, abnormal CSF flow in the syrinx group was characterized by slower and shorter downflow in a CSF flow circle, with the difference being more
significant at the foramen magnum and C-7 levels. Abnormal CSF flow dynamics has been demonstrated in patients with syringomyelia and CM-I. Reports in the literature noted that disturbance or obstruction of CSF flow by tonsillar herniation across the foramen magnum could be the leading cause for the formation of syringomyelia associated with CM-I, and the CSF flow pathology may contribute to the symptomatology independent of tonsillar ectopia; indeed, symptomatology was shown to correlate with degree of CSF flow change rather than degree of tonsillar ectopia. In addition, changes of abnormal CSF flow dynamics also closely related to the outcome after neurological decompression surgery in patients with syringomyelia and CM-I. After posterior fossa decompression, abnormal CSF flow reverts to normal and parallels symptomatic improvement with syringomyelia decreased in size.

The most widely accepted treatment for syringomyelia today is the removal of the blockage of CSF flow rather than the placement of shunts. Tubbs et al. emphasized that the goals of neurosurgical intervention in these patients were to restore nearly normal hydrodynamics of CSF flow across the foramen magnum and noted that surgeons should not perform excessive osseous structure decompression, but instead, explore and restore the pathway of CSF flow for symptoms and syringomyelia resolution. McGirt et al. examined 130 patients with CM-I to identify novel predictors of outcome after posterior fossa decompression, and the results showed that pa-

**TABLE 1: Comparison of PC-cine MRI findings between the control group and the syrinx group**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Foramen Magnum</th>
<th>C-7</th>
<th>T-7</th>
<th>L-1</th>
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<tbody>
<tr>
<td></td>
<td>Control</td>
<td>Syrinx</td>
<td>Control</td>
<td>Syrinx</td>
</tr>
<tr>
<td>UF (%)</td>
<td>57.53 ± 14.24</td>
<td>68.72 ± 24.53</td>
<td>44.40 ± 9.18</td>
<td>53.28 ± 14.72</td>
</tr>
<tr>
<td>DF (%)</td>
<td>39.73 ± 13.49</td>
<td>21.76 ± 9.71†</td>
<td>27.38 ± 8.28</td>
<td>19.35 ± 8.21†</td>
</tr>
<tr>
<td>SP (%)</td>
<td>2.76 ± 0.24</td>
<td>9.45 ± 2.24†</td>
<td>28.35 ± 5.53</td>
<td>27.51 ± 9.48</td>
</tr>
<tr>
<td>VU&lt;sub&gt;max&lt;/sub&gt; (cm/sec)</td>
<td>3.10 ± 0.71</td>
<td>2.23 ± 1.01†</td>
<td>3.81 ± 0.92</td>
<td>2.51 ± 0.62†</td>
</tr>
<tr>
<td>VD&lt;sub&gt;max&lt;/sub&gt; (cm/sec)</td>
<td>−2.91 ± 0.42</td>
<td>−1.77 ± 0.51†</td>
<td>−3.62 ± 0.47</td>
<td>−1.17 ± 0.24†</td>
</tr>
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</table>

* Values represent mean ± SD. Abbreviation: NA = data not available.
† Significantly different from the control group (p < 0.05).
patients with abnormal hindbrain CSF flow preoperatively responded better to operation, following improvement of dynamic CSF flow and resolution of symptoms. However, associated scoliosis was one of the leading risk factors for the recurrence of symptoms postoperatively.

In patients with severe scoliosis associated with syringomyelia and CM-I, the CSF downflow at the foramen magnum level was also significantly restricted. It suggested that the CSF flow pathway from the cranial to the cervical canal was narrowed or partially obstructed, due to the herniation of the cerebellar tonsils. Furthermore, a prolonged stationary phase in scoliosis patients, compared with syrinx patients, indicated a deterioration of CSF flow obstruction at the foramen magnum level. We postulated that scoliosis—especially large-curve scoliosis—would aggravate the mechanical pressure from the cerebellar tonsils at the foramen magnum and influence the CSF flow, based on the following considerations. 1) Scoliosis is a 3D deformity, involving displacement and torsion of the spinal column on the coronal, sagittal, and axial planes. During the period of scoliosis formation and progression in young patients, the relative length between the spinal cord and the spinal column could be changed considerably. Porter also suggested that there existed growth imbalance between the spinal column and the spinal cord in scoliosis patients. In recent years, Chu et al. reported that in patients with severe adolescent idiopathic scoliosis, the ratio of the length of the spinal cord to the length of the spinal column was significantly lower than in healthy controls, indicating that the growth of the neural elements in patients with idiopathic scoliosis did not match the growth of osseous elements. 2) The ill-matched length might lead to tension on the spinal cord. Around the apex region of scoliosis patients, the spinal cord was consistently located on the concave side in the spinal canal, which would minimize tension due to imbalance. 3) Substantial unresolved tension on the cord might cause downward migration of the cerebellar tonsils. Chu et al. also observed that the level of the cerebellar tonsils was lower in patients with large-curve scoliosis than in the normal population. To date it is generally agreed that, because of preexisting spinal cord tension, there has been a high rate of neurological complications during scoliosis correction procedures in patients with syringomyelia and CM-I. When scoliosis is associated with syringomyelia and CM-I, the obstruction of CSF flow at the craniocervical junction will be adversely affected.

In our previous studies, we reported on a series of patients who had scoliosis associated with syringomyelia and CM-I and underwent one-stage posterior vertebral column resection for deformity correction without suboccipital decompression. Our opinion was inconsistent with currently advocated concepts. However, in the present study, the average correction rate of scoliosis was 59.3%, and no iatrogenic neurological deterioration was encountered during the surgical procedure or follow-up. Furthermore, assessment of postoperative CSF flow dynamics demonstrated that, compared with preoperative measurements, the peak velocity of CSF flow at the foramen magnum increased, and downflow phase duration was markedly prolonged. The parameters measured demonstrated a return to near-normal CSF dynamics in the craniocervical region, which persisted through 6 or 12 months of follow-up.

We attributed the improvement in CSF dynamics to our application of the posterior vertebral column resection procedure. In our experience, this technique creates a space for spinal correction and spinal cord tension adjustment, and the correction can be performed under direct inspection and by palpation of the tension in the spinal cord.

### TABLE 2: Comparison of PC-cine MRI findings between the control group and the scoliosis group

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Foramen Magnum</th>
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<th>L-1</th>
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<tr>
<td></td>
<td>Control</td>
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<tr>
<td>UF (%)</td>
<td>57.53 ± 14.24</td>
<td>58.22 ± 8.65</td>
<td>44.40 ± 9.18</td>
<td>49.31 ± 10.33</td>
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<tr>
<td>SP (%)</td>
<td>2.76 ± 0.24</td>
<td>20.47 ± 5.29*</td>
<td>28.35 ± 5.53</td>
<td>22.76 ± 12.32</td>
</tr>
<tr>
<td>VU_{max} (cm/sec)</td>
<td>3.10 ± 0.71</td>
<td>2.75 ± 0.83</td>
<td>3.81 ± 0.92</td>
<td>3.52 ± 0.53</td>
</tr>
<tr>
<td>VD_{max} (cm/sec)</td>
<td>-2.91 ± 0.42</td>
<td>-1.67 ± 0.17*</td>
<td>-3.62 ± 0.47</td>
<td>-3.91 ± 1.49</td>
</tr>
</tbody>
</table>

* Significantly different from the control group (p < 0.05).

### TABLE 3: Comparison of the PC-cine MRI findings between the syrinx group and the scoliosis group

<table>
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<tr>
<th>Parameter</th>
<th>Foramen Magnum</th>
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<th>Syrinx</th>
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<td>Control</td>
<td>Scoliosis</td>
<td>Control</td>
<td>Scoliosis</td>
<td>Syrinx</td>
<td>Scoliosis</td>
</tr>
<tr>
<td>UF (%)</td>
<td>68.72 ± 24.53</td>
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<td>49.31 ± 10.33</td>
<td>35.03 ± 11.32</td>
<td>52.19 ± 21.45</td>
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<tr>
<td>SP (%)</td>
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</tr>
<tr>
<td>VU_{max} (cm/sec)</td>
<td>2.23 ± 1.01</td>
<td>2.75 ± 0.83</td>
<td>2.51 ± 0.62</td>
<td>3.52 ± 0.53</td>
<td>3.43 ± 0.85</td>
<td>10.31 ± 2.03*</td>
</tr>
<tr>
<td>VD_{max} (cm/sec)</td>
<td>-1.77 ± 0.51</td>
<td>-1.67 ± 0.17</td>
<td>-1.17 ± 0.24</td>
<td>-3.91 ± 1.49*</td>
<td>-3.78 ± 1.02</td>
<td>-6.82 ± 2.77*</td>
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</table>

* Significantly different from the syrinx group (p < 0.05).
During the procedure, the focus of the correction process is on the spinal cord, which is protected from excessive tension and stretching by the shortening of the spinal column. Following posterior vertebral column resection, the tension of the spinal cord at the craniocervical junction was decreased in our patients, and abnormal CSF flow was indirectly improved.

Postoperatively, most patients showed a significant decrease (> 30%) in syrinx size. The improved CSF flow dynamics must play the important role in the reduction in syrinx size. With respect to tension of the spinal cord, some researchers have noted that the formation of syringomyelia was related to excessive tension on the spinal cord. Royo Salvador held that the formation of syringomyelia in patients with CM might be caused by distraction of the spinal cord—through the development of an ischemic focus in the central part of the spinal cord at the cervical spine, and then syringomyelia formation. Iskandar et al. also found that syringomyelia was not related to cord compression or arachnoiditis, and distraction of the spinal cord was one of the leading causes in the formation of syringomyelia. More recently, Hsu et al. reported on syringomyelia associated with tethering of the spinal cord. The syringomyelia was located in the caudal third of the cord and could be resolved after the tethered spinal cord was released. The authors postulated that the tethered spinal cord was correlated with the formation of syringomyelia. We propose that reduction of the cord tension improved the CSF flow dynamics at the craniocervical junction in our series and contributed to syrinx resolution, which was similar to the postoperative change with neurosurgical decompression. In addition, the resolution of previous neural dysfunction might be related to the reduction of the cord tension and syrinx resolution.

In the present study, we not only observed the CSF flow changes at the craniocervical junction and in the cervical spine, but also attempted to observe CSF flow changes in the thoracic and lumbar spine (Tables 1–3). In the syrinx group, the peak velocity of CSF flow at the T-7 level was higher than normal. In the scoliosis group, the peak velocity of CSF flow at the apex level was the highest among the 3 groups; this finding was probably related to the small space occupied by the spinal cord within the canal and the decrease in compliance of the subarachnoid space. However, at the L-1 level, the direction of flow (up or down) often reversed quickly, making the CSF flow pattern heterogeneous. The reference values of the measured parameters decreased significantly. In addition, there were differences in the measurement of CSF flow changes in the literature, likely caused by different magnetic intensity, technical parameters, and slices of MRI used in different studies. These could have influenced the space resolution and signal-to-noise ratio and made the imaging findings inconsistent. The present study revealed that the measurement of CSF flow velocity at the craniocervical junction in the control group was close to the results of Ünal et al. (single directional peak flow velocity 4.70 ± 1.61 cm/sec) and by Liu et al. (peak flow velocities 2.45 ± 0.67 cm/sec and 1.79 ± 1.15 cm/sec), who used the same type of MRI scanner as was used in this study.

With respect to the limitations of this study, the small

| TABLE 4: Comparison of the preoperative and postoperative PC-cine MRI findings in the scoliosis group |
|---------------------------------------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| Parameter                                          | Foramen Magnum         | C-7                   | Foramen Magnum         | C-7                   | Foramen Magnum         | C-7                   |
|                                                   | Preop | 3 Wks Postop | 6–12 Mos Postop | Preop | 3 Wks Postop | 6–12 Mos Postop | Preop | 3 Wks Postop | 6–12 Mos Postop |
| UF (%)                                             | 58.22 ± 8.65 | 46.49 ± 18.75 | 50.22 ± 16.38 | 49.31 ± 10.33 | 50.12 ± 21.34 | 51.34 ± 18.64 |
| DF (%)                                             | 21.55 ± 11.32 | 38.40 ± 9.27* | 36.54 ± 7.75 | 28.77 ± 10.29 | 33.81 ± 10.21 | 32.63 ± 11.30 |
| SP (%)                                             | 20.47 ± 5.29 | 15.11 ± 6.20 | 13.35 ± 8.25 | 22.76 ± 12.32 | 17.51 ± 7.45 | 16.52 ± 5.86 |
| VU_{max} (cm/sec)                                  | 2.75 ± 0.83 | 3.52 ± 0.27* | 3.12 ± 0.34 | 3.52 ± 0.53 | 3.68 ± 1.02 | 3.47 ± 0.62 |
| VD_{max} (cm/sec)                                  | −1.67 ± 0.17 | −2.41 ± 0.25* | −2.67 ± 0.52 | −3.91 ± 1.49 | −3.15 ± 0.87 | −3.34 ± 0.49 |

* Significant difference between the parameters at different time points (p < 0.05).
sample size did not allow us to use the statistical methods of correlation or regression to analyze the relationship of correction rate, syrinx shrinkage, and neurological changes. We suggest that in the future, more patients with scoliosis associated with syringomyelia should be included, and they should be followed up for a longer period to observe the changes in postoperative CSF flow dynamics and to assess changes in the syrinx and neurological function. In addition, animal models could be used to test changes in CSF flow dynamics during the formation of syringomyelia and scoliosis. These studies will be helpful in clarifying the relationship between tension of the spinal cord and the formation of syringomyelia and scoliosis.

Conclusions

In the present study, we compared CSF flow dynamics in the subarachnoid space between patients with CM-I and scoliosis patients without CM-I and syringomyelia associated with scoliosis. Syringomyelic patients (that is, patients in the scoliosis group and the syrinx group) presented with CSF flow obstruction at the craniovertebral junction, and the obstruction may be aggravated by associated severe scoliosis. This is the first report of CSF dynamic research following one-stage posterior vertebral column resection rather than neurosurgical decompression for spinal deformity correction in scoliosis patients with syringomyelia. Recovery of dynamic flow acts as a crucial factor for postoperative syrinx shrinkage. This might be related to the procedure of spinal shortening and cord tension reducing though posterior vertebral column resection, which indirectly relieved CSF flow obstruction on foramen magnum.

Disclosure

The authors report that they received no grants or outside funding for their research or preparation of this manuscript and that no commercial entity paid or directed, or agreed to pay or direct, any benefits to any research fund, foundation, education institution, or other charitable or nonprofit organization with which the authors are affiliated.

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Accepted January 23, 2013.
Please include this information when citing this paper: published online March 1, 2013; DOI: 10.3171/2013.1.SPINE12366.
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